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The Influence of Holding Device Anchor Parameters On The Holding Force Magnitude, Of An Integrated Linear Electromagnetic Motor

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---ABSTRACT--
This paper investigates the influence of the design parameters of the upper ferromagnetic shunt, namely the value of the holding area S_H ,that creates a holding force F_H , equal to that in breakaway stage in magnitude of this holding force at the breakaway stage. The design of an integrated circuit and the equivalent magnetic circuit of the integrated LEMM on breakaway stage was built, mathematical models of system were laid out. The most acceptable range of these ranges of magnitude of holding area is $S_H^* \geq 0.2 \ldots 0.4$, and this happens when $\Phi_{ush}^* = 0.2 \ldots 0.4$ .The resulting holding force will vary in range of $(0.05 \ldots 0.15)$ to $(0.2 \ldots 0.55)$.

***INDEX TERMS:* Holding force, holding area, holding device, break away stage, upper shunt, lower shunt, anchor**

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I. INTRODUCTION

One way of increasing specific power and energy performance of pulsed electromagnetic linear motors (LEMM) reciprocation that implement multiple pulse technology is forced accumulation of magnetic energy in the working clearances pulse LEMM on the breakaway anchors (armature) stage due to the delay (retention) of its movement. In this case, the appearance and increase of the current in the windings of the motor anchor stay for a while in a stationary state, in spite of the increasing tractive force of working clearances due to static loading motor, the anchor is held by electromagnetic device. Anchor starts to move with increased initial tractive force. The holding force F_H regulation achieved by motor design, is quite simple and has a wide range of F_H available by changing current in the coil of the holding electromagnet device supplied from a separate source [1, 2].

The desire to simplify the design of pulse LEMM while increasing its specific power and energy performance, have led to the idea of integrated design of the motor, through better holding device of anchor based on the same magnetic core and the same magnetic motive force mmf [3, 4, 5].

II. PROBLEM STATEMENT

In such motor design, anchor on breakaway stage is held by its own magnetic field ferromagnetic guide housing 2 Fig.1, which is called an upper magnetic shunt relative to the upper running clearance δ_u . Lower magnetic shunt is a ferromagnetic anchor guide 3. Thus, the LEMM in this design has two working clearances shunted by motor parts design - the upper and lower magnetic shunts. During operation in this LEMM with holding device (holding device integrated in design), both shunts saturate an eventually affect motor performance . Experimental studies of such integrated LEMM showed that the regulation of holding force is difficult because it depends on several design parameters of the motor.

This paper investigates the influence of the design parameters of the upper ferromagnetic shunt, namely the value of the holding area S_H , that creates a holding force, equal to that in breakaway stage in magnitude of this holding force at the breakaway stage. In this LEMM design, holding force F_H occurs between mating surfaces, which is formed by the upper part of the flat anchor 1 and the top of the inside of the ferromagnetic shunt (2) when they are in contact or almost in contact the gap δ_0 .

III. MATHEMATICAL MODELS OF SYSTEM

In such a motor design, when we connect the coil to the power supply for the first time and until the initial magnetic field has not yet unfolded, both the magnetic shunts are also not saturated and have small magnetic reluctance R_{ush} R_{Lsh} , hence $R_{ush} = R_{ush\,1} + R_{ush\,2}$.

From the equivalent of the magnetic circuit LEMM and with neglecting the leakage flux Fig.2 which is corresponding to the design scheme in Fig. 1, the magnetic flux Φ_{yo} yoke 5 appears as two components:

$$\Phi_{yo} = \Phi_{ush} + \Phi_{\delta u} = \Phi_{Lsh} + \Phi_{\delta L} \qquad (1)$$

these two components pass in the anchor LEMM almost entirely through the upper shunt (R_{ush} and $R_{up\,\delta}$), bypassing the upper working clearances δ_u , which in this case have much bigger reluctance $R_{\delta u}$ compared to the reluctance of the upper branch of the R_{ub} shunt Fig.2 and the technological gap Δ:

$$R_{ub} = R_{ush} + R_{up\,\delta} \qquad (2)$$

$$R_{up\,\delta} = \frac{\delta_{up}}{\mu_0 S_H};$$

$$R_{\Delta} = \frac{\Delta}{\mu_0 S_{upsh}} \qquad (3)$$

Where $R_{up\,\delta}$, the reluctance of the air gap δ_{up} , creates the holding force and forms mating surfaces of the upper shunt and the top of the anchor 1 .

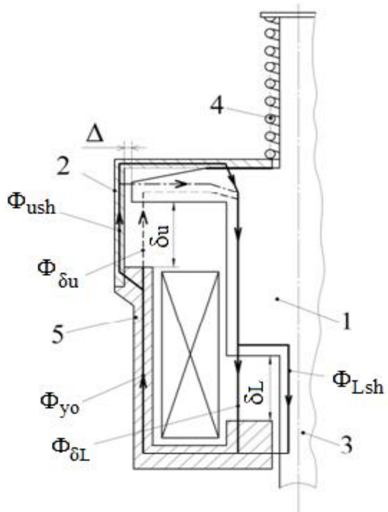

Figure 1 The Design of An Integrated Circuit LEMM.

$R_{up\,\delta}$ at a given moment is much smaller than shunt R_{ush} ; due to minimal value of air gap δ_{up} , which is selected in the initial state of a return spring 4 and smaller than the reluctance technological gap R_{Δ} .
Therefore, the expressions (1) and (2) can be written as:

$$\Phi_{yo} \approx \Phi_{ush} \quad ; \quad R_{ub} = R_{ush}$$

Then by the electromagnetic holding force which occurs between the upper shunt and the upper shunt of part anchor, the anchor is attracted to the stationary shunt, and despite the increase of the current in the coil anchor it is held in this position. The magnitude of holding force F_H in this case depends on the magnitude of the magnetic flux of the upper shunt Φ_{ush} and its contact area with the flat part of the anchor - (Holding area) S_H (in Fig.1 shows a heavy line). The magnitude Φ_{ush} with a certain saturation induction B_0 material of the guide housing (upper shunt) is determined by its cross-sectional area S_{ush}. Accordingly, the value of holding force under these conditions will be a function of two design parameters - area S_H and area S_{ush}.

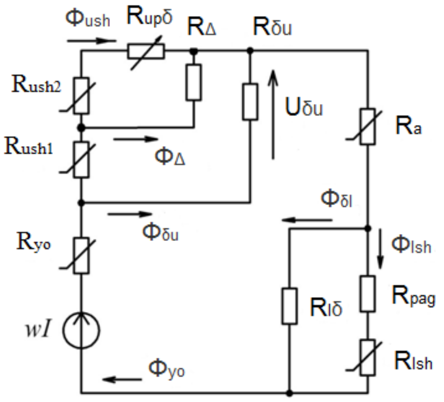

Figure 2 The Equivalent Magnetic Circuit of The Integrated LEMM on Breakaway Stage

With increasing mmf winding wi on breakaway anchors stage, the magnetic flux of the upper shunt Φ_{ush} also increases. Thus, the holding force increases and saturates this ferromagnetic shunt, and reluctance R_{ush} begins to increase. As a result, shunt flux slowdown and a simultaneous redistribution of Φ_{ush} and $\Phi_{\delta u}$ occurs according to equation (1). That is, all the bulk of the flux in the yoke Φ_{yo} in particular the flux component $\Phi_{\delta u}$ extends through upper working clearance (the dotted line in Fig.1) which is represented by $R_{\delta u}$ element in the equivalent magnetic circuit (Fig.2), that creates additional tractive force down, acting on a combined anchor 1 motor. Similar processes occur in the lower shunt with the difference that it is saturated before the upper shunt, and the reluctance of the parasitic air gap R_{pag} Fig.2 remains unchanged when the motor is operated and accordingly the tractive force in the parasitic air gap is not created.

Anchor LEMM is pulled out from the holding area of upper shunt and begins to move when the sum of traction forces of the upper $F_{\delta u}$ and lower $F_{\delta l}$ running clearances (excluding leakage flux) exceeds the holding force of the upper shunt F_H :

$$F_H < F_{\delta u} + F_{\delta l} \qquad (4)$$

To assess the effect of parameters design of the upper shunt at breakaway moment of anchor, and to express each of the components (4) we use Maxwell formula for one working air clearance . Then (4) takes the form:

$$\frac{\Phi_{ush}^2}{2\mu_0 S_H} < \frac{\Phi_{\delta u}^2}{2\mu_0 S_{\delta u}} + \frac{\Phi_{\delta l}^2}{2\mu_0 S_{\delta l}}, \qquad (5)$$

where $S_{\delta u}$, $S_{\delta l}$ are the areas of the upper and lower working clearances of LEMM respectively.

Substitute flux $\Phi_{\delta u} = \Phi_{yo} - \Phi_{ush}$ in equation (5). Assuming $S_{\delta u} = S_{\delta l} = S_{yo} = S_a$ and fluxes $\Phi_{\delta u} = \Phi_{yo}$ result in the following equation :

$$\frac{\Phi_{ush}^2}{S_H} < \frac{(\Phi_{yo} - \Phi_{ush})^2}{S_{yo}} + \frac{\Phi_{yo}^2}{S_{yo}} \qquad (6)$$

Approximately fluxes $\Phi_{\delta l} = \Phi_{yo}$ are equal when lower shunt is saturated. Overstating tractive force in the lower working clearance is justified by the fact that, the leakage fluxes, which are neglected in the analysis, participate in the creation of tractive force of the motor in the breakaway stage. Taking Φ_{ush}, relative to Φ_{yo} and S_{ush}, S_H relative to the S_{yo} the following equation results:

$$\Phi^*_{ush} = \frac{\Phi_{ush}}{\Phi_{yo}}, \; S^*_{ush} = \frac{S_{ush}}{S_{yo}}, \; S^*_H = \frac{S_H}{S_{yo}}$$

Solving this equation with respect to Φ^*_{ush} we get:

$$\Phi^*_{ush} < \frac{-1 + \sqrt{\frac{2}{S^*_H} - 1}}{\frac{1}{S^*_H} - 1} \qquad (7)$$

An expression similar to equation (7) is obtained in [6].

From equation (7), it is clear that the dependence of holding force F_H upper shunt on the value of the holding area S_H through various values of the saturated flux of the upper shunt Φ_{ush} .

To express the holding force F_H in relative terms $F^*_H = \frac{F_H}{F_{bas}}$ it is appropriate to use a tractive force of LEMM with two working clearances based on Maxwell formula.

The tractive force in Maxwells equation is equal twice the value of traction force of one of the working air gaps, in the upper shunt or lower.

The upper shunt is used in following equation

$$F_{bas} = 2F_{\delta u} = \frac{\Phi^2_{\delta u}}{\mu_0 S_{yo}}$$

Then the holding force is expressed as:

$$F^*_H = \frac{F_H}{F_{bas}} = \frac{\Phi^2_{ush}\mu_0 S_{yo}}{2\mu_0 S_H \Phi^2_{\delta u}} = \frac{\Phi^2_{ush} S_{yo}}{2 S_H (\Phi_{yo} - \Phi_{ush})^2}$$

After the rearranging above equation we get :

$$F^*_H = \frac{\Phi^2_{ush} S_{yo}}{2 S^*_H (1 - \Phi^*_{ush})^2} \qquad (8)$$

In formula (8), parameter $\Phi^*_{ush} = \frac{\Phi_{ush}}{\Phi_{yo}}$ can be considered as saturation flux which occurs in the upper shunt .

As shown in Fig.3 and with reference to equation (8) , $F^*_H = f(S^*_H)$ when $\Phi^*_{ush} = const$, which clarify the influence of the values of holding area of the upper shunt on holding force, when upper shunt is saturated.

The analysis shows that with increasing the magnitude of S^*_H , the holding force F^*_H decrease and thus becomes more stable. This is due to the decrease of the magnetic induction in the air clearance. The magnetic induction in the air clearance influence the force F_H more than S_H .

It is evident from each curve in Fig. 3 which correspond to a small change of magnitude of shunt saturation flux , $\Phi^*_{ush} = 0.1 ... 0.2$, that with small portion of shunt S^*_{ush} , there are two different changeable sizes for F^*_H , such that when you change S^*_H there will be two areas one represents significant change and the other represents negligible one in the curve F^*_H .

From Fig.3 , it is indicated that the first portion of changes in F^*_H cannot be used for the purpose of regulating the energy stroke LEMM, but it is possible to use $\Phi^*_{ush} > 0.2$ for this purpose.

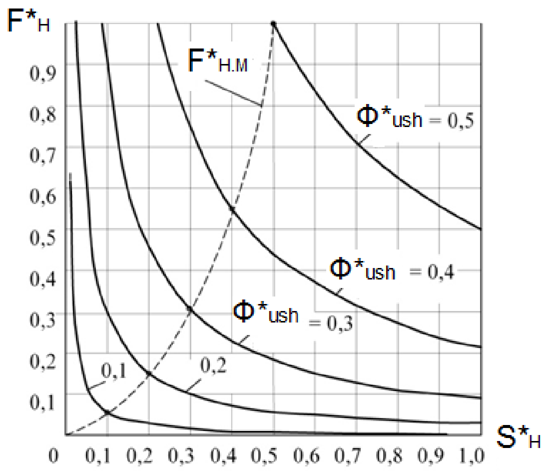

Figure 3 The Influence of Magnitude of Holding Area S_H and Magnetic Flux Shunt Φ_{ush} on Holding Force Anchor F_H

During the process of regulating the energy of the LEMM working stroke the holding force should be less than tractive force, therefore, the area of the graph in Fig.3, corresponds to $F_H^* > 1$, should not be used.

Since the magnetic flux lines Φ_{ush} on breakaway anchor stage LEMM, include portions of a ferromagnetic guide housing 1 and holding area 2 with cross-sections S_{ush} and S_H, then, taking the induction values $B_0 = B_H$ of these sections we obtain the same flux Φ_{ush} for the same values of cross-sections $S_H = S_{ush}$.

As indicated by the next equation, the values expressed in relative terms will be equal:

$$\Phi_{ush}^* = S_H^* = S_{ush}^* \qquad (9)$$

Solving equation (8) for F_H^*, to determine the maximum holding force under the condition implemented in equation (9) the following equation results:

$$F_{H.M}^* = \frac{0.5 S_H^*}{(1 - S_H^*)^2} \qquad (10)$$

Equation (10) gives the range for design parameters values for holding device of the motor. The maximum value for the holding force is shown as a dotted line in Fig.3 .

To the left of the dotted line in fig.3 combination of parameters S_H^*, Φ_{ush}^* and S_H^* cannot be calculated, because of the saturation of the magnetic shunt and the holding area. This saturation leads to a decrease in F_H, therefore it is advised to saturate the holding area after ferromagnetic guide housing, by the means of greater inductions and magnetic flux respectively.

This can be achieved either by overstating section $S_H (S_H > S_{ush})$, or by higher saturation magnetic flux density of the material area at the same section S_H. For these reasons, the combination of parameters is possible to the right of the dotted line. Thus holding force can be regulated by using, for example, a removable washer as proposed in [3, 4].

The most acceptable range of the magnitude of holding area is $S_H^* \geq 0.2 \ldots 0.4$, and this happens when $\Phi_{ush}^* = 0.2 \ldots 0.4$. The resulting holding force will vary in the range of $(0.05 \ldots 0.15)$ to $(0.2 \ldots 0.55)$, above values for holding area will allow regulating the energy in working stroke of pulse LEMM at high efficiency during the static loading of the motor [7]. The relations obtained are used in the design calculations of pulse LEMM with an integrated holding device of anchor.

IV. CONCLUSION

Implementation of the forced accumulation of magnetic energy in an integrated LEMM on breakaway anchor stage can be achieved only by certain range of parameters of the holding device anchor and the shunt. The ranges of the magnitude of holding area is $S_H^* \geq 0.2 \ldots 0,4$, and this happens when $\Phi_{ush}^* = 0.2 \ldots 0,4$ The resulting holding force will vary in the range of $(0.05 \ldots 0.15)$ to $(0.2 \ldots 0.55)$. Increasing sectional area of the upper shunt S_{ush}^* and decreasing the magnitude of holding area S_H^* according to above ranges of parameters will increase the magnetic induction of the yoke, starting the anchor to move with increased initial value of the tractive force LEMM.

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